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NAVAL POSTGRADUATE SCHOOL
Monterey, California

IMPROVED EFFICIENCY AND POWER DENSITY FOR THERMOACOUSTIC COOLERS

by

Thomas J. Hofler

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This report was prepared for the Office of Naval Research, ONR 331, Arlington, VA.

The report was prepared by:

Thomas J. Hofler
Thomas J. Hofler
Research Assistant Professor
Department of Physics

Reviewed by:

W. B. Colson
William B. Colson, Chairman
Department of Physics

Released by:

P J Marto
Paul J. Marto
Dean of Research

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Thomas J. Hofler

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Naval Postgradute School
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A new design for a thermoacoustic heat driven cooler is proposed and has been analyzed via a numerical model. The engine layout incorporates a half wavelength or can be run in a full wavelength with dual prime movers and dual coolers coupled thermally in parallel.

Both simplified models and more physically realistic models have been constructed and adjusted for good performance. Simplified models indicate an overall COP of 0.48, which means that the total cooling power is a factor of 0.48 smaller than the total heat input. More detailed and realistic models indicate an overall COP of 0.43. Geometry numbers have been finalized and much of the drafting for an experimental unit has been completed. We hope that high power densities can be achieved with this engine. We also believe that overall COP's in the range of 0.6 to 0.7 may be possible with further improvements.

Additionally, we have numerically studied issues of achieving acoustic onset with this engine and the sensitivity of the onset condition to the model parameters.

We have also developed a new heat exchanger fabrication method which will allow us to achieve the smallness of geometry scale that was discussed in the previous report. The practical result is better thermal coupling with less acoustic dissipation. The fabrication method is also considerably simpler than our previous method.

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Improved Efficiency and Power Density for Thermoacoustic Coolers

June 1995

by

Thomas J. Hofler
Physics Department
Naval Postgraduate School
Code PH/HF
Monterey, CA 93943

for

Office of Naval Research
Dr. Logan E. Hargrove ONR 331
Navy Environmentally Safe Ships Program

ABSTRACT

A new design for a thermoacoustic heat driven cooler is proposed and has been analyzed via a numerical model. The engine layout incorporates a half acoustic wavelength or can be run in a full wavelength with dual prime movers and dual coolers coupled thermally in parallel.

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Improved Efficiency and Power Density for Thermoacoustic Coolers

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I Project Description

The goal of the proposed basic research is to consider and evaluate new thermoacoustic cooler designs which will lead to substantial improvements in both efficiency and cooling power density. The specific design aspects to be considered are the acoustic resonator, the stack, and the internal heat exchangers. Substantial improvements in both the efficiency and the cooling power density of thermoacoustic refrigerators is necessary in order for the technology to be competitive with existing refrigeration technology.

II Approaches Taken

Reasonably high cooling power densities can be obtained if high acoustic amplitudes and high mean pressures can be used effectively. Acoustic amplitudes having a peak dynamic pressure that is at least 10% of the mean pressure are necessary ($p_o/p_m = 0.1$) and a value of 20% or higher is desirable. While the acoustic loss for heat exchangers may be a modest fraction of the total acoustic power for low amplitude engines, it is much larger for high amplitude engines. For some high amplitude heat exchanger designs, the acoustic loss generated by both hot and cold heat exchangers could be the dominant source of loss in the entire system, or at least the largest single source of loss in the system.

Theoretical and experimental investigations of thermoacoustic heat exchanger performance has been reported in the previous summary report. These results show that very short heat exchangers having low acoustic loss can still be thermally effective, if they have the proper plate or fin separation. Our heat exchanger efforts this year have focused on the task on <u>constructing</u> the best possible heat exchangers for experimental engine prototypes having high cooling power density.

In a new direction this year, we have completed an initial computational investigation of a new thermoacoustic engine topology. ("Topology" here refers to the general physical layout or organization of the various engine components.) The new engine is a heat driven cooler and is functionally similar to the original design by Wheatley and Hofler.[1] The advantages of a thermoacoustic heat driven cooler are that very high acoustic amplitudes and power densities can be achieved fairly simply, thus avoiding a major engineering effort in electrodynamic drivers. Also, such engines have no moving parts and may be very reliable, and vibration is reduced with the elimination of the accelerated piston mass found in electrodynamic drivers. While the energy conversion efficiency for a thermoacoustic driver is less than that of an electrodynamic driver, the efficiency of electric power generation is often less than 50%.

There are two main advantages of the new engine topology compared to the original design.[1] First, and most important, the positions of the prime mover stack and cooler stack in the acoustic standing wave, can be optimized independently. Second, the performance of the prime mover stack is improved slightly by forcing the acoustic power to flow in a direction that is opposite that of the heat flow. Sometimes referred to as a "Stirling effect;" this geometrical arrangement uses the acoustic phase shift between pressure and velocity that occurs near a pressure antinode to enhance the acoustic power generation rather than allowing the phase shift to decrease acoustic power generation.

III Summary of Completed Work

Numerical Analysis

A simplified numerical model of the new engine topology was constructed. See section IV for more detail on the configuration of the heat driven cooler. Assuming temperatures of 400° C, 27° C, and −13° C for the hot, ambient, and cold temperatures respectively; overall COP's as high as 0.47 were obtained. This means that the cooling power is 0.47 times as large as the heat input. Although simplified, this model is similar to an experimental device that we are currently constructing. There is also some modeling evidence that more advanced improvements could yield overall COP's in the range of 0.6 to 0.7.

The numerical model was subsequently modified to more closely conform to the actual hardware that we are now constructing. This more complicated model indicated that an overall COP of 0.43 should be possible for our experimental device. Correctly modeling all of the hardware details shows that the efficiency is reduced slightly by these details, but we can also determine the effect of these hardware details on the reactive acoustic wave. Unanticipated changes in the reactive acoustic wave can adversely affect the engine optimization.

The detailed model was also used for a parameter sensitivity analysis. It was found that the acoustic power balance between the output of the prime mover and the dissipation of the cooler is extremely sensitive to the position of the acoustic pressure antinode (PAN) relative to the stacks.

Heat Exchanger Fabrication

In accordance with the previous summary report, we plan to use finned heat exchangers that are short in the wave propagation direction and have fin separations that are very small. For the new heat driven cooler under construction, the ideal fins separations are approximately 125 microns. We have devised a new heat exchanger fabrication technique and have more-or-less perfected it. <u>We have successfully made an exchanger with fin separations of 125 microns, and the</u>

uniformity of the separations are better than 10%. While these numbers sound impressive, the finished part is even more impressive to see under magnification. Also, the new fabrication technique is considerably faster and easier to implement compared to our previous methods.

The new heat exchangers will necessarily incorporate additional thermal structures coupled to the fins. This is essential for the purpose of minimizing the heat conduction distance and temperature drop along the lengths of the fins, when the thermal power density is high. We have explored two different structures: one with excellent thermal performance (ie. low effective thermal resistance), but difficult to fabricate; and one with mediocre thermal performance and simple construction. We currently plan to use the simple one for the initial experiments, and consider fabrication alternatives for the more complicated structures for possible use in follow-on experiments.

Engine Construction

At this point, over half of the drafting for the experimental engine is finished, nearly all of the materials and subcomponents have been acquired, and we hope to begin machining soon.

We have taken some initial steps towards some simple experimentation with alternate stack structures for use in the prime mover. While these stacks are suitable for high temperature use, the first tests will be with a cryogenic prime mover because the apparatus already exists. We hope to have the experiment running in a few weeks. The alternate stack structure should greatly reduce solid thermal conduction. This is discussed briefly in section V.

Miscellaneous

The demonstration refrigerator project was finished by Lt. Berhow in his Master's thesis project. This easily portable device cools down to 0° C in about 2 min., has an ultimate cold temperature of -21° C, and maximum cooling power of about 15 Watts. This objective was to quickly produce frost on a visible, uninsulated portion, of the refrigerator.

The experimentally measured COP's are in excess of 1.0, and the COP relative to Carnot peaks at about 12%. These numbers are based on externally measured temperatures. The peak COP relative to Carnot predicted by numerical analysis is about 20%, based on internal temperatures. These two efficiency numbers are consistent with anticipated temperature defects in the heat exchangers, although these defects were not measured.

Mr. Adeff and I have experimentally tested two more variations of our thermoacoustic cryocooler design. We have finally broken our old temperature span

record slightly and have achieved our best span of 120° C. These measurements also confirm the concept of combined Stirling and thermoacoustic heat transport components. In these measurements, acoustic phase shifts were used to enhance the Stirling component and improve the temperature span.

IV Heat Driven Cooler Topologies

The original Wheatley/Hofler topology is shown in Fig. 1. It is effectively a quarter wavelength design. The advantages of this design are simplicity and compactness, and the sensible location of the three different temperatures. In this design, the three major temperature differences are all separated by the stacks. This tends to minimize nuisance heat leaks compared to the new topology, discussed below.

The disadvantage of the old design is that the prime mover and cooler stacks must fit into mutually exclusive regions of the standing wave. Typically, for small temperature span thermoacoustic engines, the stack performs best when it occupies a region in the standing wave extending from 0.08 to 0.2 radians, measured from the pressure antinode (PAN). This is more or less true for both prime mover stacks and for cooler stacks. Hence, in the old design, the prime mover stack is too close to the PAN and the cooler stack is too far from the PAN for optimal performance. The overall COP for this topology is quite poor and is in the range of 0.05 to 0.1.

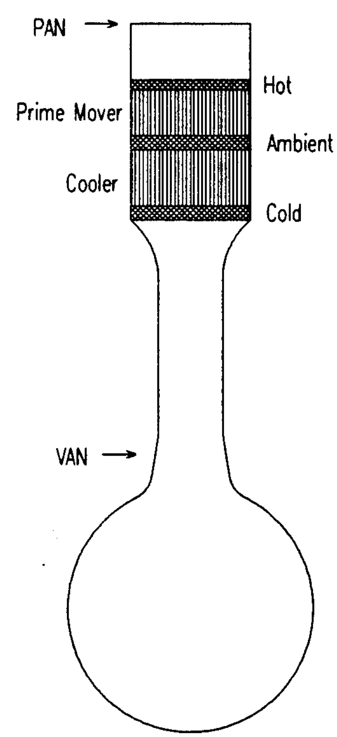

Figure 1. Wheatley/Hofler Heat Driven Cooler

Two versions of the new topology are shown in Fig. 2. The simplest version, shown in Fig. 2a, is a half wavelength design, and has the pressure antinode located in the middle of a duct, with the prime mover and cooler stacks located on opposite sides of the PAN. This arrangement has the major advantage of allowing the locations of the stacks to be optimized independently of each other. It also has the disadvantage of creating a new path for a nuisance heat leak, flowing from the hot heat exchanger, through the PAN, to the ambient exchanger of the cooler section.

Some of this nuisance heat leak will be caused by diffusive conduction through the gas and solid materials. Through careful mechanical design, the amount of diffusive conduction can be held to small but non-negligible level. As the engine is scaled up in size and power, the amount of diffusive conduction should be further reduced in relative terms.

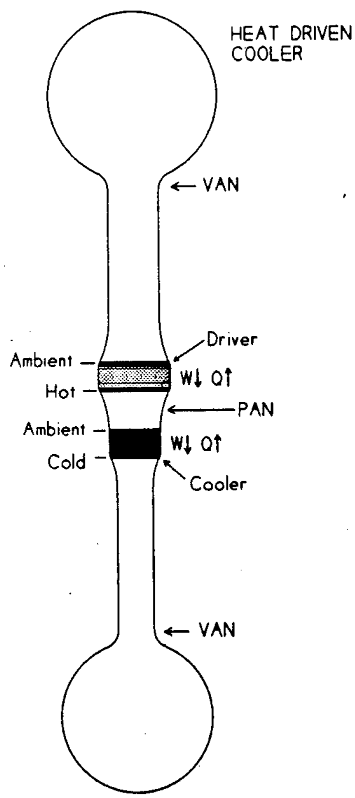

Figure 2a. New Half-Wave Heat Driven Cooler

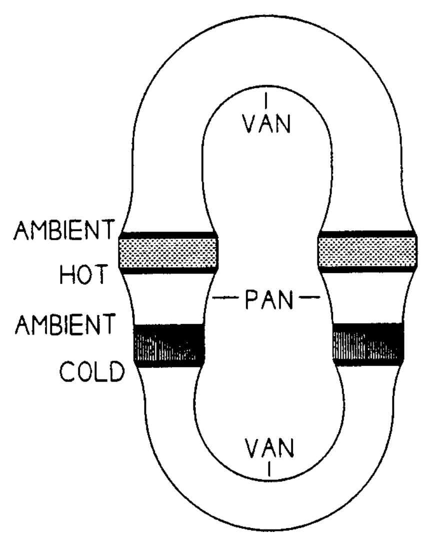

Figure 2b. Dual Full-Wave Version

The heat leak through the PAN region of the tube may also be driven by nonlinear convective processes (streaming), and these are not readily calculable. However, we do not anticipate very large amounts of convectively driven heat transfer through the PAN region, since the acoustic velocity there is very small, even compared to the velocities in the stacks.

A secondary advantage of the new topology is that the direction of the heat flow in the prime mover stack is opposite that of the acoustic power flow in this stack. (While there is a small amount of acoustic power flowing upward in Fig. 2, most of it flowing downward toward the cooler section of the engine.) This means that the stack channel size can be reduced slightly and the efficiency increased slightly, because the phasing between pressure and velocity causes an additional Stirling effect. In the new design, the "Stirling" component of acoustic power generation in the prime mover contributes to the dominant thermoacoustic component; whereas in the old design, it subtracts from the thermoacoustic component reducing the efficiency.

The new topology shown in Fig. 2b is a "dual" full wavelength version of the half wavelength version shown in Fig. 2a. It is essentially two half wavelength engines joined together. In addition to doubling the power level, the dual version has the advantage of eliminating the bulky spheres required for the single half wavelength version. These spheres also exact a small, but significant reduction in the efficiency at low acoustic amplitudes and possibly a larger reduction at high amplitudes. The latter nonlinear inefficiency may arise from flow separation problems at the tube/sphere junctions.

V Heat Driven Cooler Analysis

There is perhaps little to be gained by an in-depth discussion of the analysis, prior to the initial experimental measurements. The following summarizes the basic premise and assumptions of the analysis and some of the results.

Modeling half the "dual" engine

The initial simple analysis of the new topology was accomplished by building a numerical model of half of the "dual" engine shown in Fig. 2b. The portion modeled is from one velocity antinode to the other velocity antinode. In other words, a vertical section of Fig. 2b down the middle would produce two identical halves, and this simple model analyzes one of those halves.

Note that the engine of Fig. 2a is not only more complicated to model but it is less efficient. It is less efficient not only because the spheres dissipate acoustic energy, but because acoustic impedance of the spheres require the connecting tubes to be longer than ones used in the simple model.

Other assumptions were: temperatures of 400° C, 27° C, and −13° C for the hot, ambient, and cold temperatures respectively; a 4" diameter prime mover and a 3" diameter cooler; 15 atmospheres of helium pressure; a peak pressure that is 10% of the mean pressure; and 500 Hz operation. Details that were ignored were: thermal conduction in the resonator tube walls; some heat exchanger details

including the thermal defects of the heat exchangers (acoustic dissipation of the exchangers was included); and some stack performance details.

This last detail concerns the nature of the prime move stack. It was assumed to use the same type of construction as the cooler stack, namely a plastic parallel-plate (or spiral roll) configuration. Clearly, no plastic will tolerate the hot temperatures of the prime mover. We hope to use a stainless steel prime mover stack configuration, that is not parallel-plate, and that has very low thermal conduction. A stainless steel parallel-plate stack would have very large amounts of diffusive conduction. The prime mover stack structure we intend to use should conduct heat at a level that is nearly negligible, and thus be similar to plastic.

The best results for this model indicate an overall COP of 0.47. Overall COP is the ratio of available cooling power to the total heat input. Various modifications (some of which have been modeled) can improve the efficiency further. These would include increasing the hot temperature and increasing the overall size of the engine.

Modeling the "single" engine

While the engine of Fig. 2a, is more complicated to model, it is much simpler to construct and is more likely to perform as anticipated. A more complicated numerical model was constructed of this topology as a design tool for the initial experimental device.

Roughly speaking, this model is similar to the simple model with tube tapers and spheres added. The assumptions and omissions for this model were the same as previously discussed except for the following: the operating frequency was lowered to 350 Hz and much more heat exchanger detail was included. Also, much more diagnostic information was generated by the model.

The operating frequency was lowered and the length of the engine increased, because the conduction heat leak along the tube wall through the PAN region was too large. The addition of the extra resonator components and heat exchanger components brought the number of geometry input values up from 29 to 55. This more realistic model brought the overall COP down to 0.43, which is not too bad considering the extra component "baggage."

There are two related critical issues in the operation of the experimental engine. The first issue is the question of achieving acoustic onset with the cooler stack having zero temperature gradient. The cooler stack will have its largest acoustic load and the prime mover will have to be heated to much higher temperatures in order to achieve onset.

The second issue is the location of the PAN relative to the two stacks in the experimental engine. Achieving the proper location requires that the model accurately reflect the experiment, which is the primary reason for including all 55

input geometry values mentioned above. However, it also requires that the temperatures of the higher velocity portions of the resonator be precisely controlled. These considerations give rise to the question, "How sensitive is the performance of the engine to the location of the PAN?"

A parameter sensitivity analysis done with the numerical model shows that it is very sensitive indeed. A small shift in the position of the PAN (on the order of 0.1% of the engine length) can cause a substantial increase in the acoustic power output of the prime mover and a decrease in the acoustic power consumption of the cooler, with reduced efficiency overall. This makes onset easier to achieve. A small shift in the opposite direction has the opposite effect on the power balance and onset is not achieved.

There are two philosophical viewpoints in pondering the results of this sensitivity analysis. One viewpoint is that there is a problem in achieving the desired PAN location for optimal engine efficiency. The second viewpoint is that this topology has a virtue which is that, given a means to shift the location of the PAN slightly, the acoustic onset problem at engine startup can be solved. While we prefer the latter viewpoint, only experimentation will identify the real problem areas and their severity.

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Principal Investigator: Thomas J. Hofler

Mailing Address: Naval Postgraduate School
Code PH/Hf
Monterey, CA 93943-5117

Phone Number (with Area Code): 408-656-2420

E-Mail Address: hofler@physics.nps.navy.mil

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Grad Student Asian e/n ____
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Post-Doc Minority ____
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VII Publications

Contributed Conference Presentations

Thomas J. Hofler, "Numerical study of various thermoacoustic refrigerator configerations." J. Acoust. Soc. Am. Vol. 96, No. 5, Pt. 2, p. 3220, Nov. 1994, Austin Texas.

Invited Presentations

Thomas J. Hofler, "Thermoacoustic Refrigeration." Stanford University, Fluid Mechanics Seminar, April 1995, Palo Alto, CA.

Patents Granted

D. A. Brown, S. L. Garrett, and T. Hofler, "Fiber-optic flexural disk accelerometer," U. S. Patent 5,317,929, granted June 7, 1994.

Thomas J. Hofler, David A. Brown, and Steven L. Garrett, "Fiber optic accelerometer with centrally supported flexural disk." U.S. Patent 5,369,485 granted Nov. 29, 1994.

Supervised Theses

"Construction and performance measurement of a portable thermoacoustic refrigerator demonstration apparatus," Todd J. Berhow, Lieutenant, USN, Master of Science in Applied Physics, December 1994, thesis advisor.

"A mass element resonator for a small temperature span thermoacoustic refrigerator," Erin A. Wilson, Lieutenant, USN, Master of Science in Physics, December 1994, thesis advisor.

IX References

1. John C. Wheatley, G. W. Swift, A. Migliori, and T. Hofler, "Heat-driven acoustic cooling engine having no moving parts," U.S. Patent 4,858,441 granted 1989.

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